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DEVELOPMENT OF AN APPARATUS FOR BIAXIAL AND SHEAR STRESS-STRAIN TESTING OF FABRICS AND FILMS

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UNITED STATES ARMY
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This report describes the design, construction and evaluation of an apparatus for the measurement of the behavior of fabrics under biaxial tensile and shear forces. The instrument was evaluated by the testing of fabrics ranging in weight from 34 g/m^2 to 486 g/m^2, corresponding to material applications ranging from lightweight parachute fabrics to heavyweight ballistic fabrics. The testwork demonstrates that the instrument, within the limitations of the testing techniques developed to date, can be used to provide the information necessary for → cont.

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cont the design of structural fabrics, the drafting of improved procurement specifications for fabrics and qualification of new fabrics for military applications. Technical problems and limitations of the instrument and of the testing techniques which require further study are discussed.

FOREWORD

In October 1975 a program was initiated to design a new fabric testing instrument which simultaneously measures the shear and biaxial stress-strain behavior. The program was undertaken by the US Army Natick Research and Development Laboratories (NLABS) with funds provided by the US Army Materials and Mechanics Research Center (USAMMRC) under the Materials Testing Technology (MTT) Program. The work was accomplished under three separate PRON numbers as follows:

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DEVELOPMENT OF AN APPARATUS FOR BIAXIAL AND SHEAR STRESS-STRAIN TESTING OF FABRICS AND FILMS

INTRODUCTION

At the present time the mechanical behavior of fabrics is generally defined in terms of the load-deformation behavior measured under uniaxial load. This definition is not realistic for structural fabrics since, for example, the loads on a tent fabric are transferred to the support structure through concurrent biaxial and shear stresses. Studies conducted by Bolt, Beranek & Newman[1] on the structural analysis of frame-supported tents and by the NLABS[2] on the structural analysis of pressure-stabilized beams and arches have clearly demonstrated the need for a complete description of the fabric stress-strain behavior including shear stiffness in such analysis. At this time such knowledge and understanding of the biaxial and shear behavior of fabrics is inadequate for application to our development efforts and to fabric specifications for procurement. In addition, apparatus currently available for measuring the mechanical behavior of fabrics[3,4] is inadequate because test formats are limited to a small number of biaxial stress ratios and do not include shear deformation. Thus a new apparatus is needed for the measurement of the complete stress-strain behavior of fabrics.

The purpose of this report is to describe a study whose objective was the design, construction and evaluation of an apparatus for the measurement of the complete stress-strain behavior of fabrics needed for design analysis and procurement specification of structural fabrics and which can also be used to insure that the fabric specifications are met during procurements. This report will discuss apparatus design and construction, development of test procedures and evaluation of capability. To evaluate the capability of the apparatus, results will be presented from the testing of a lightweight parachute fabric, a medium weight tent fabric, a heavyweight body armor fabric, and the standard FWWMR-treated cotton canvas tent duck. The test results on these four fabrics will show the capabilitity of the apparatus for testing the range of fabric weights of interest to the Army.

[1] Paul J. Remington, John C. O'Callahan, and Richard Madden; Analysis of Stresses and Deflections in Frame Supported Tents; US Army Natick Laboratories Technical Report TR 75–31; 1974 (AD A002072)

[2] Earl C. Steeves; A Linear Analysis of the Deformation of Pressure Stabilized Beams; US Army Natick Laboratories Technical Report TR 75–47; 1975 (AD A006493)

[3] Constantin J. Monego; The Biaxial Stress-Strain Behavior of Fabrics; US Army Natick Laboratories Technical Report TR–ME–4; 1965 (AD625255)

[4] R.E. Sebring and W.D. Freeston, Jr.; Biaxial Tensile Tester for Fabrics, US Army Natick Laboratories Technical Report TR 67–71–GP, 1967 (AD 658684)

DESIGN AND CONSTRUCTION DETAILS

Among the design alternatives considered for an apparatus to simultaneously measure the biaxial and shear stress-strain properties of fabrics, the pressurized cylinder design appears to be the most attractive and was selected for this project. The pressurized cylinder is inherently in a biaxial stress state and the cylinder geometry facilitates shear deformation through torsion. However, the ratio of the circumferential stress to the axial stress in the pressurized cylinder is 2 and the possible test formats are therefore limited unless axial loads are applied simultaneously with the pressurization. This is what was done in the present design with the axial load and pressure applied so as to maintain a constant ratio between the circumferential and axial stresses. The design of this apparatus can be described in terms of three elements of the apparatus which must be coordinated to accomplish the objective. These elements are the cylindrical specimen and bulkheads, the biaxial stressing mechanism, and the torsion mechanism.

Cylindrical Specimen and Bulkheads

We begin here with a discussion of the preparation of the fabric specimen. A cylinder diameter of 10 cm was chosen and since, except in rare cases, flat fabrics are what we have to test, these flat goods must be made into cylinders. Two techniques for forming cylinders are available – sewing and adhesive bonding – and both were used in this program although sewing appears to be the better of the two.

Sewing is the most common and convenient method of making a cylinder from a flat fabric. It is recognized that the resulting seam in a fabric cylinder which consists of two or four layers of cloth plus sewing thread will react to stress differently than the rest of the fabric. However, by keeping the width of the seam small, 0.652 cm, in relation to the circumference, 31.4 cm, or only 2% of the circumference of the cylinder, the effect on biaxial stress-strain properties of the fabric should be negligible. Furthermore, the test technique to be used will impose an axial deformation on the cylinder; the stress will be computed from the resulting axial load, and the effect of the additional fabric in the seam can be included in this calculation.

With regard to the strength of the seams, work conducted at NARADCOM over the past 32 years has shown that sewn seams can be made as strong as, or stronger than, the base fabric. In discussing the details of seam sewing we cite the following documents:

1) Federal Standard 191a, Textile Test Methods, Method Number 5110, Sewability of Woven Cloth; Seam Efficiency Method.

2) Federal Standard 751a, Stitches, Seams, and Stitching.

3) Federal Specification V–T–285D, Thread, Polyester.

Federal Standard 191a, Method 5110, is the method of comparing the strength of fabric seams versus the strength of the fabric. Federal Standard 751a defines all of the stitch and

seam types in industrial use and available for this program. Research on seams and stitching has shown that the Type 401 stitch set forth in this document would yield under stress before failing, thus absorbing energy. The Type 401 stitch was selected for this program because of its energy absorbing properties. Polyester thread was selected for this program because of its high strength, relatively low weight, and the fact that most of the fabrics to be evaluated are made of continuous filament synthetic fibers. To obtain maximum seam strength, two rows of stitchings are made with a two-needle machine with the stitch rows spaced 0.652 cm apart.

Strength of seams so made can be estimated by the following empirical expression:

Theoretical Seam Strength = Thread Strength (newtons) x 2 x 1.6 x Stitches per cm

The values for the above expression are obtained as follows: The thread strength is obtained from Federal Specification V–T–285D for polyester thread. The value 2 stands for two rows of stitching; the value 1.6 is experimentally determined for polyester thread; the number of stitches per centimeter is machine adjustable. Suggested techniques including thread size, needle size, stitches per centimeter and seam types for sewing the range of fabric weights of interest are given in Table 1. To verify the strength of the seaming techniques chosen cylinders were made from three fabrics, all having a weight of less than 136 g/m^2, and sewn using the techniques given in Table 2. These cylinders were inflated until failure occurred. All of the resulting failures occurred away from the seam, as illustrated in Figure 1, demonstrating that the seam did not represent a weakness in the cylinder.

In preliminary testing of fabrics covering a wide range of weights, we found that these sewing techniques worked well for light and medium weight fabrics and even for heavyweight fabrics when the test was not carried to rupture. However, in attempts to test heavyweight fabrics to failure with 1/1 stress ratio conditions, the seams in the sleeves failed with pressure. These failures were the result of the weave yarns pulling out from under the stitching threads. We then used a binding agent to prevent this yarn slippage, and this was successful in that it allowed testing to proceed to the point where the stitching threads failed indicating a need for stronger thread. Because of the lack of a sewing machine to accept heavier and stronger thread, this remedy has not been evaluated, although a sewing machine has been ordered. In addition, we have looked at different types of seams to give increased seam strength. One that looks promising is illustrated in Figure 2. This seam is made by sewing the cylinder through the three layers as shown and then turning the cylinder inside out. Further study of seaming for high strength fabric is needed.

Coated fabrics can be seamed using these same sewing techniques but the seams so produced are not airtight as required for pressurization. A better means of seaming coated fabrics is either by using cements, or if adaptable, heat-sealing techniques. Cementing and heat sealing techniques will provide airtight seams. With coated fabrics the ideal way of making seams is by heat-sealing, if the elastomeric coating is adaptable to this method. However, heat-sealing equipment is expensive and is restrictive as to elastomers which can be heat-sealed. From a research point of view the cost of heat-sealing equipment is prohibitive and recourse has to be taken to the alternative method of using adhesives. In the use of adhesives a study must be made to determine the adhesive which will accomplish the objective desired. In this

TABLE 1

Seaming of Fabrics

Fabric Weight g/m^2	Thread Size[a]	Needle Size[b]	Stitches/cm	Seam Type[c]
136	B	0.036	4.8	LSC–2
272	E	0.044	4.0	LSC–2
408	F	0.048	3.2	LSC–2
544	FF	0.051	2.4	LSC–2

TABLE 2

Seaming Lightweight Fabric Cylinders

Fabric Weight g/m^2	Thread Size[a]	Needle Size[b]	Stitches/cm	Seam Type[c]
34.0	B	0.036	4.6	LSC–2
44.0	B	0.036	4.2	LSC–2
115.0	B	0.030	4.2	LSC–2

[a]Federal Specification V–T-285D, Thread, Polyester

[b]Inches measured across the blade at the needle hole position

[c]Federal Standard No. 751a, Stitches, Seams and Stitching

FIGURE 1. FABRIC SLEEVE TEST SHOWING FABRIC FAILURE AWAY FROM SEWN SEAM

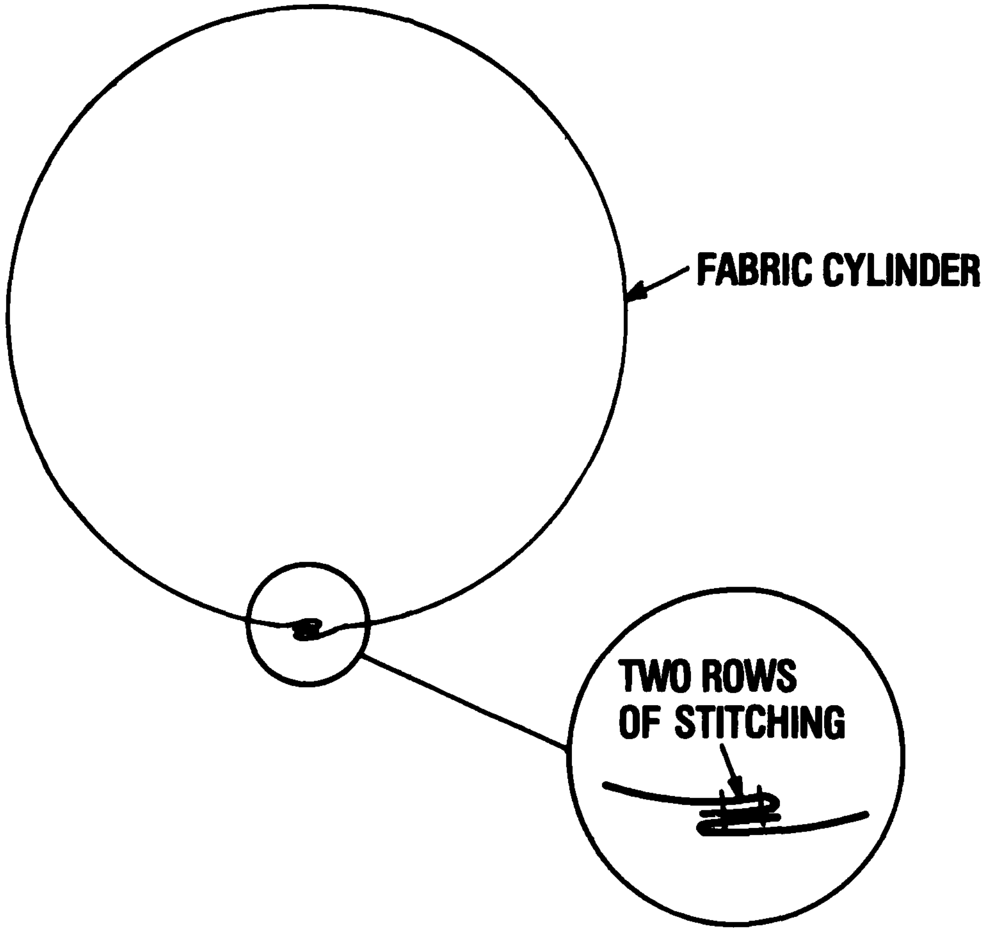

FIGURE 2. ALTERNATE SEAMING TECHNIQUE

study a lightweight nylon polyurethane fabric was used to provide an impermeable fabric for tests. It was desirable for this cloth to make an air-impermeable seam. While the seam in this fabric could be made by heat-sealing, the inexpensive way of accomplishing this was by cementing the seams. This required that a suitable cement be found and tested to obtain the desired result. Of the many cements available for cementing polurethane film, three were found worthy of further testing to obtain the seam strengths needed for this program. All three cements were made by the USM Corporation, Bostik Chemical Division. The criterion for cementing seams was that a 25.4-mm-wide seam must have a tensile strength equal to that of the fabric. In actual practice, seams of 12.5 mm and 25.4 mm were made and tested. The test results are given in Table 3. Where three types of specimen failures are shown: a coating failure, cement failure and fabric break. The first is a coating failure where the coating separates from the fabric at the seam. This phenomenon is indicative of a low coating adhesion due either to a defect in the fabric or to the adhesive softening the coating and weakening the bond between the coating and the fabric. The second is a cement failure which occurred with one of the adhesives tested. It is not understood why this type of failure should occur only with the widest seam made. The third mode of failure is the fabric break. This is the desired criterion, since the break occurred away from the seam, indicating that the seam is stronger than the fabric. The results shown on Table 3 indicate that Bostik 7376 is more consistent in making seams stronger than the fabric than the other two adhesives, particularly in the narrow 12.5 mm width. Therefore, Bostik 7376 was selected for the use in this program. Suitable cementing techniques would have to be found for each different elastomer used to coat the fabrics.

Having techniques for making cylindrical fabric specimens, it is necessary to design bulkheads to close the ends of the cylinders. These bulkheads must provide a pneumatic seal so that the cylinder can be pressurized and must restrain the ends of the cylindrical specimen against the pressure and axial load. The initial design of the bulkheads is shown in Figure 3 and is included here to show the details regarding end fittings for connection to the Instron Tension Tester and the location of the thrust bearing to allow rotation of the cylinder about its axis for torsion tests. These aspects of the design stayed essentially constant through all the redesigns which dealt with the sealing and securing of the fabric specimen to the bulkheads. An additional consideration in the design of the attachment was to get fabric failures away from the attachment or clamping device, that is, to prevent what are commonly called in uniaxial testing "jaw breaks." The redesigns included various wedge, ring and groove, and clamping configurations. The design found to be most satisfactory and in current use is one of the simplest and uses three clamps on each end with two of the clamps seated in grooves. The clamp on each end closest to the test section is not in a groove because we found that this greatly reduced the occurrence of "jaw breaks." This bulkhead design in illustrated in Figures 4 and 5. A pneumatic port was incorporated in one of the bulkheads for pressurization of the specimen.

To test uncoated fabrics, an impermeable bladder is needed and three approaches to accomplish this were examined; seamless polyethylene tubing, custom made rubber tubing, and elongated toy balloons.

In the initial work with polyethylene tube, we used tubing having a diameter of 10 cm and a thickness of 0.03 mm and found that the polyethylene does not have sufficient stretch

TABLE 3

Polyurethane Coated Nylon Fabric, Strength of Cemented Seams

Bostik Adhesive	Specimen Number	Seam Strength and Failure Mode 12.5 mm Seam Width		25.4 mm Seam Width	
70 70	1	8.06 kN/m	ca	10.12 kN/m	fa
70 70	2	8.93	ca	10.33	fa
70 70	3	7.70	ca	11.29	fa
70 70	4	8.32	ca	10.73	fa
70 70	5	8.11	ca	10.86	ca
70 70	6	7.67	ca	7.44	ca
71 33	1	7.18	ca	8.76	ce
71 33	2	5.52	ca	9.28	ce
71 33	3	4.64	ca	9.81	ce
71 33	4	4.59	ca	8.76	ce
71 33	5	3.33	ca	8.23	ce
71 33	6	5.64	ca	9.63	ce
73 76	1	10.94	fa	10.16	ca
73 76	2	11.74	fa	10.07	ca
73 76	3	11.93	fa	9.95	ca
73 76	4	11.59	fa	10.82	fa
73 76	5	11.03	fa	10.86	fa
73 76	6	11.21	fa	10.33	fa

ca – Coating failure

ce – Cement failure

fa – Fabric failure

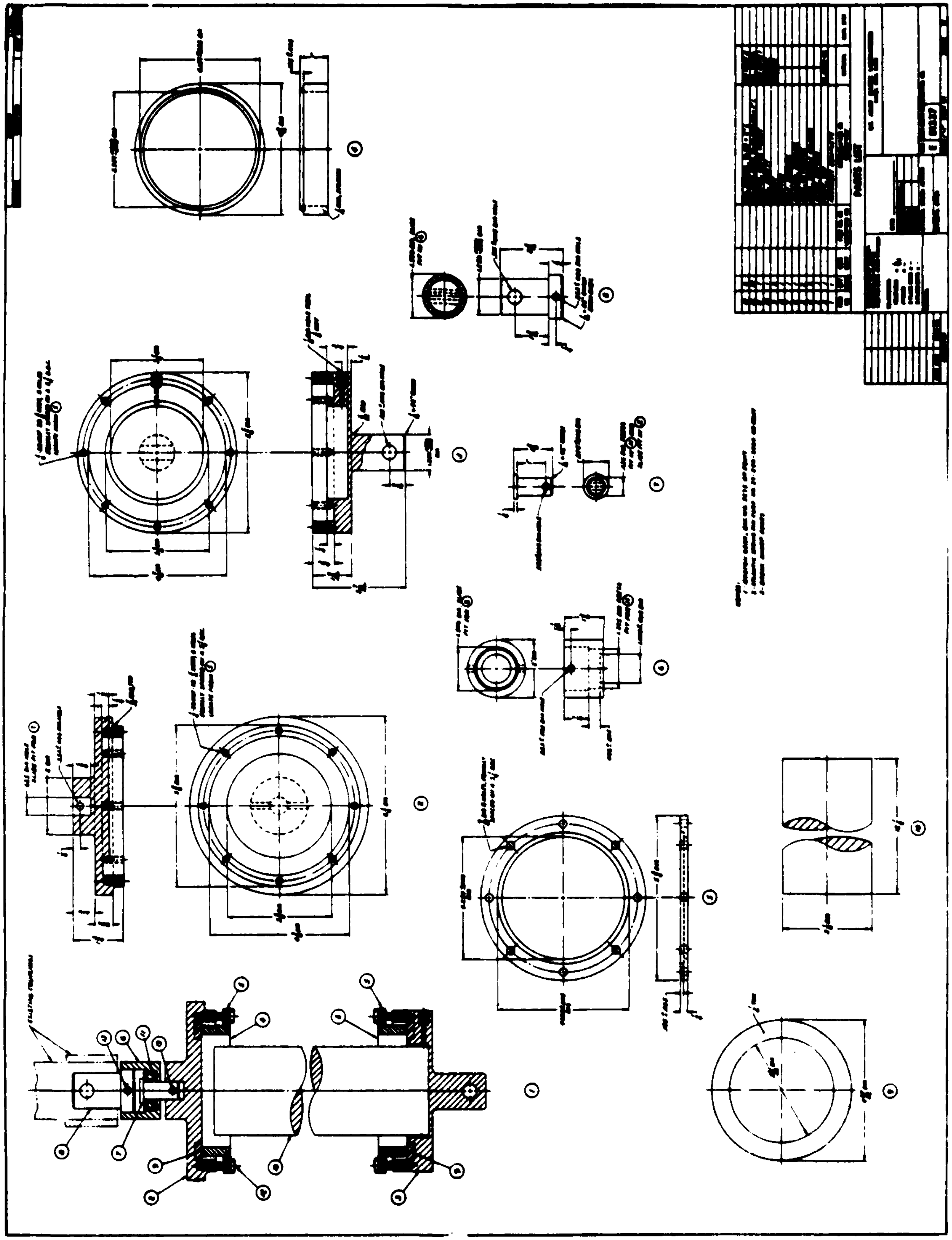

FIGURE 3. INITIAL BULKHEAD DESIGN

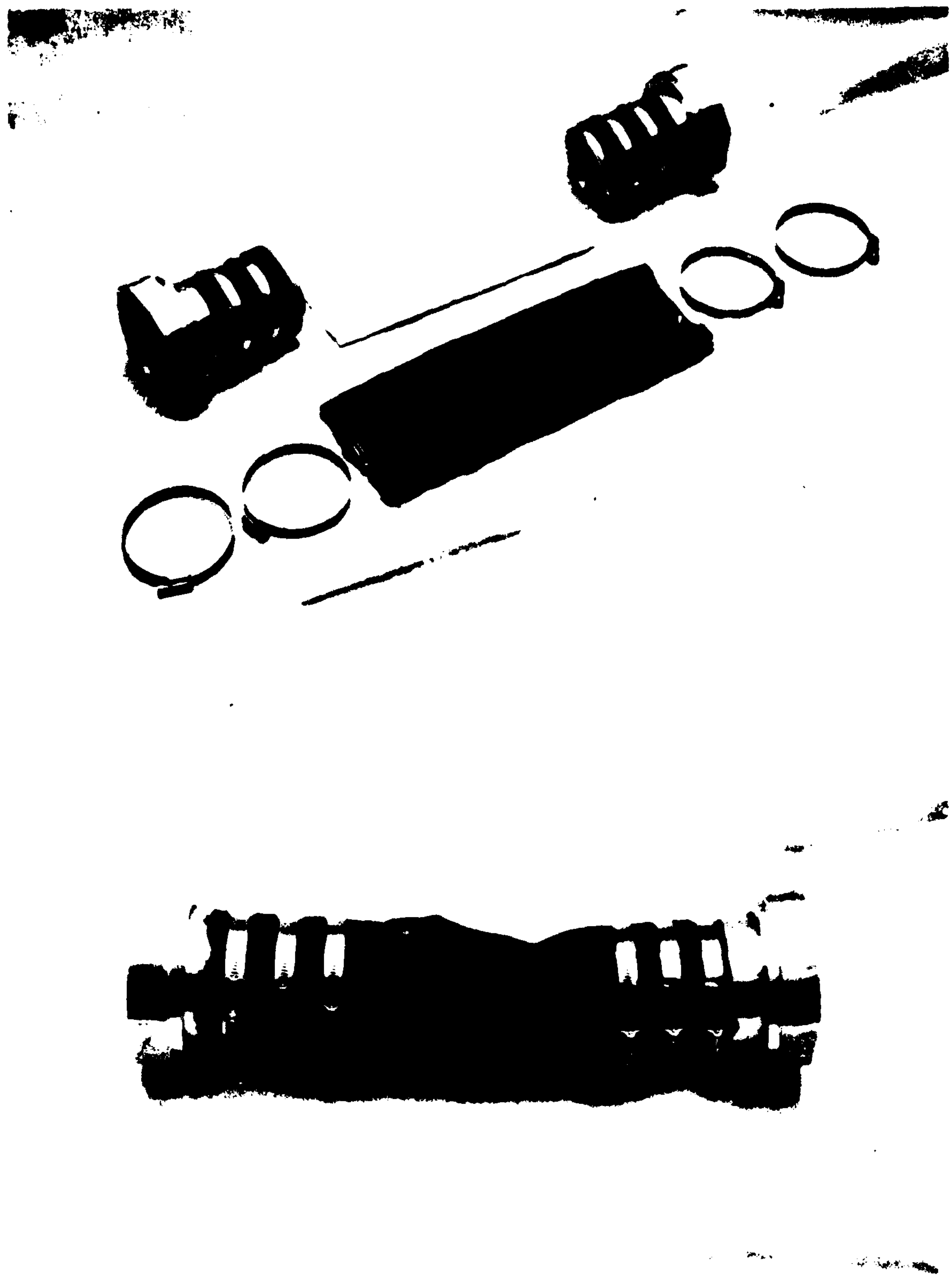

FIGURE 4. BULKHEADS TO CLOSE OFF CYLINDRICAL SPECIMEN.

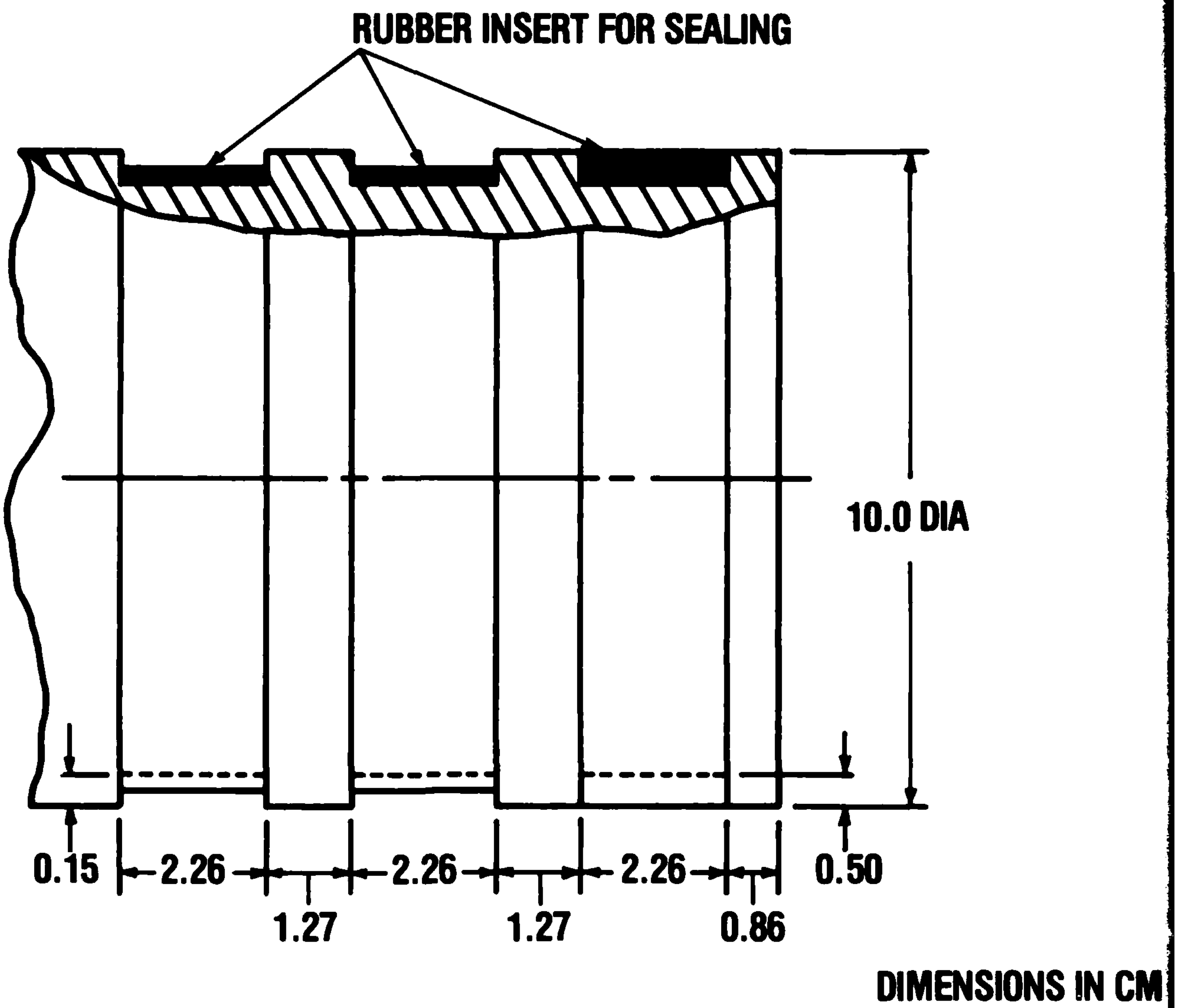

FIGURE 5. SKETCH OF BULKHEAD-FABRIC ATTACHMENT

to accommodate the breaking extension of the fabric. This resulted in premature rapture of the polyethylene bladder and loss of pressure. As a result, we changed over to 0.03-mm-thick polyethylene tubing having a diameter of 11 cm, ten percent larger than the fabric tube, and when installing this bladder, excess material was also put in along the axis of the cylinder. This excess material was allowed to wrinkle in the cylinder and thus provide a bladder with additional ability to elongate through the unwrinkling of the material. Use of this technique gave reasonable results, and it is felt that the polyethylene tubing was moderately successful, but further testing is required to determine whether its use will prove to be completely suitable. The reason for using the polyethylene tubing is that its cost is much lower than making rubber tubes to fit the cylinders. However, with the not totally successful use of polyethylene tubing, we procured some custom-made latex rubber bladders. These bladders were made on a dipping mandrel. The first tubes obtained were thicker than desired and had extremely short storage life, developing cracks and cuts, so they were unusable. Subsequent procurements resulted in thinner tubes with longer storage life and these tubes have proved to be the most satisfactory for testing fabrics. A third impermeable material was tried, namely toy balloons, to have a completely inclosed pressure chamber. The bulkheads were modified to fit the balloons to the test chamber. The elongated balloons were tried in the testing machine. It was found, however, that the quality of these balloons was too variable and the construction of the bulkhead provided cracks and crannies for the balloons to slip into, causing premature rupture. This procedure was discontinued.

With regard to any of these bladder concepts, the question of their influence on the measurements being made arises. However, in all these concepts the bladder materials are much more flexible than the fabrics to be tested and will have negligible effect on the results related to axial or direct stresses. In the case of shear behavior, the situation is not so clear since the fabric shear stiffness is small. Although the shear stiffness of the bladder is also small, it is not yet known which will dominate. There is an additional factor that may influence the shear behavior; namely, the bladder material pressing against the fabric under the action of the pressure may lock the weaver together much as a coating would, thus changing the shear behavior. All of these questions on the influence of the bladder on the shear measurements require further experimental study.

Biaxial Load Application

As indicated above, the design chosen for biaxial loading of the fabric is the cylindrical specimen subjected to internal pressure and axial load. The application of the pressure is relatively simple in that all that is needed is a pressure source and some valves and regulators. The axial load is applied by mounting the specimen attached to the bulkheads in an Instron Tensile Testing Machine, Model 1125. In order to conduct a test that will result in useful data, the application of the pressure and the axial load must be coordinated in some way, and we chose a test format in which the ratio of the axial stress to the circumferential stress is constant throughout the test. As is typical with the Instron testing machines, the motion of the crosshead drives the test. This motion results in an axial load applied to the cylinder, and this load is measured by the Instron strain gage load transducers which give an output voltage proportional to the load. Similarly, the pressure in the cylinder is measured with a pressure transducer, which has a voltage output proportional to the pressure. These two voltages are transmitted to an electronic control device which compares them against the specified stress

ratio. When the pressure is below the level required to maintain the specified stress ratio, the control device causes a solenoid-actuated valve to open to increase the pressure. This control procedure is illustrated schematically in Figure 6 and the circuit diagram of the electronic controller is shown in Figure 7. The control law for this procedure can be obtained by writing down the expressions for the axial stress T_a and the circumferential stress T_c:

$$T_a = Pr/2 + F/2\pi r \tag{1}$$

$$T_c = Pr \tag{2}$$

where P is the pressure, F is the axial force and r is the radius of the cylinder. The control law desired is

$$T_a/T_c = \beta \tag{3}$$

where β is the specified stress ratio and the parameters that can be controlled are P and F, so that substitution of equations (1) and (2) into (3) gives

$$P = F/(2\beta - 1)\ \pi r^2 \tag{4}$$

This tells us that the pressure is related to the axial force by a constant if the radius of the cylinder remains constant, but for fabric cylinders this does not seem to be even approximately true because of the relatively large elongation which fabrics experience. Although this suggests incorporation of the cylinder radius measurement in the control, we were able to get satisfactory control without it, as is demonstrated by the data in Table 4. Given in this table are the desired or specified stress ratios for a number of tests and the average stress ratio and its standard deviation over the length of the test. It is seen that the stress ratio can be set with good accuracy for stress ratios of 1 and 2 but that the setting is rather poor for a stress ratio of 6. This can be corrected by changing the index on the controller which sets the stress ratio. The standard deviation is the critical parameter regarding performance, as it measures the variability of the stress ratio during the test and is felt to be acceptable for the lower stress ratios but is quite high when the stress ratio is set to be six. However, in all these results is included a transient start-up period during which large variation in the stress ratio occurs and this start-up period is much longer in tests with the stress ratio set at six. If this start-up period is ignored in computing the average and standard deviation, the results are acceptable with test S101–10 having an average of 6.3 and a standard deviation of 0.12 and test S102–17 having an average of 5.6 and a standard deviation of 0.08. These results show that the control without incorporating the radius measurement is acceptable. This is confirmed by an examination of the stress ratio data in detail which reveals that as the test proceeds and the radius increases in magnitude the stress ratio becomes smaller as is predicted by equation (4). This change is small, however, and acceptable.

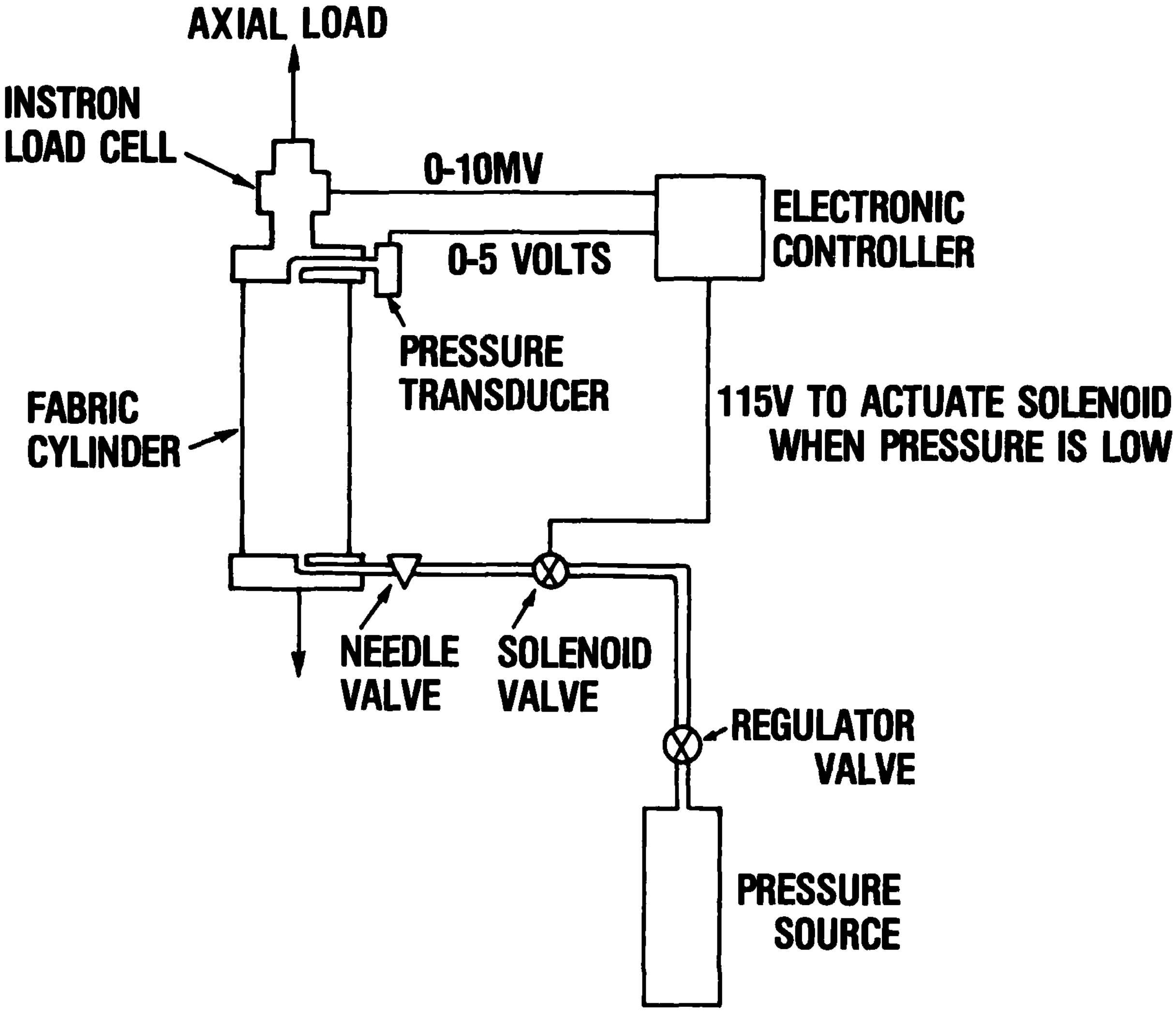

FIGURE 6. SCHEMATIC OF STRESS RATIO CONTROLLER

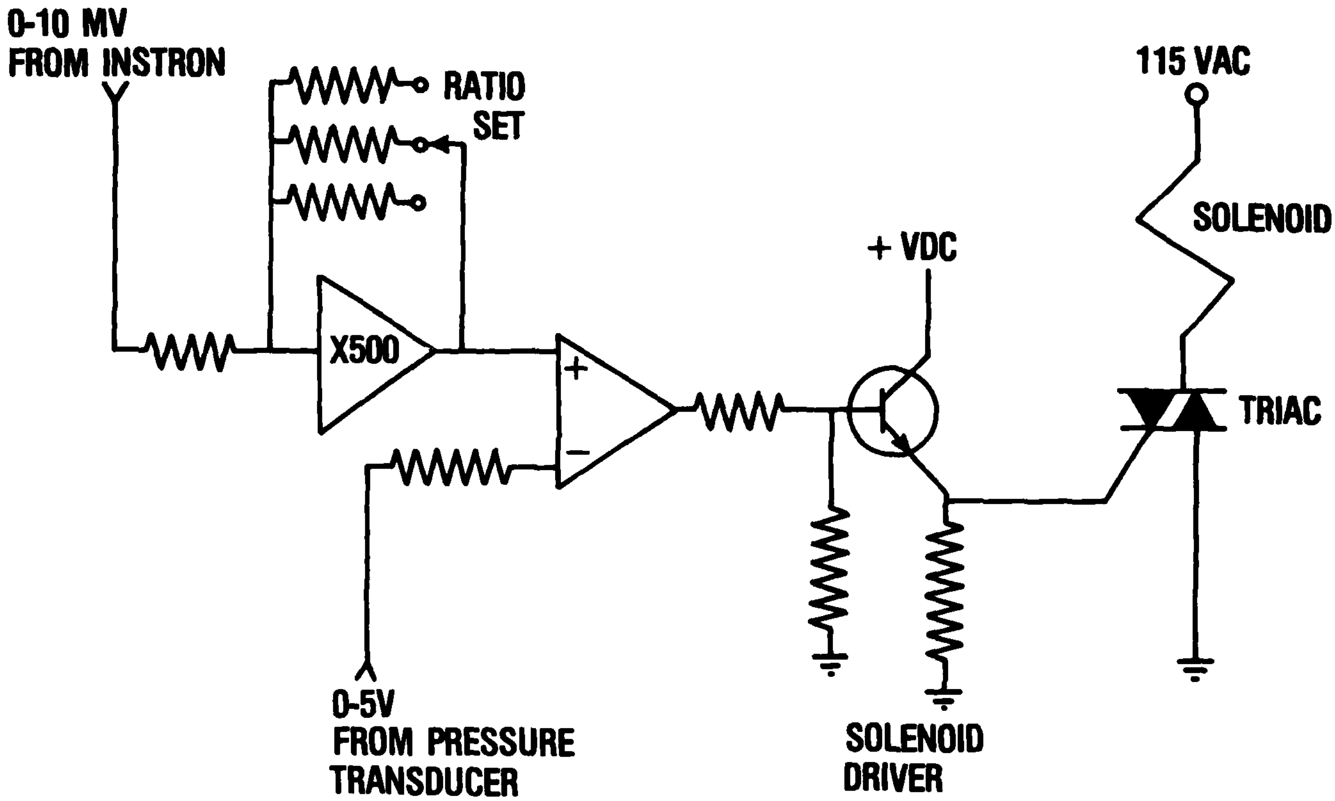

FIGURE 7. CIRCUIT DIAGRAM OF THE STRESS RATIO CONTROLLER

TABLE 4

Performance of Controller in Maintaining the Stress Ratio

Test No.	Specified Stress Ratio	Average Stress Ratio	Standard Deviation
S101–1	1.0	1.01	0.10
S101–4	1.0	1.09	0.05
S101–7	2.0	2.02	0.43
S101–10	6.0	5.29	1.75
S102–2	1.0	1.09	0.06
S102–6	1.0	1.01	0.02
S102–7	2.0	2.09	0.03
S102–17	6.0	5.02	1.12
S102–20	6.0	5.8[illegible]	0.69
S105–8	2.0	2.06	0.26

From equation (4) we derive the following expression for the stress ratio:

$$\beta = 1/2 + F/2\pi r^2 P \tag{5}$$

From this we find that the lower limit on the stress ratio is 1/2, but doing a test with this stress ratio requires that the controller maintain the axial force at the value zero. Although this was possible, it was not completely satisfactory and is not generally done. The test procedure used is to run tests with stress ratio at unity and greater on two samples, one having the cylinder axis parallel to the fabric warp yarns and the other parallel to the fill yarns. If the stress ratio is defined in terms of the stress in the warp direction and the stress in the fill direction as

$$\alpha = T_w/T_f$$

then the above procedure gives tests with α both greater than and less than unity.

Application of Shear Deformation

With the pressurized cylinder design, the application of shear deformation is quite naturally accomplished by fixing one end of the cylinder against rotation and rotating the other end. A Zeromax drive, Model J43–W2–N3, was selected to rotate the cylinder end. This drive which is shown in Figure 8 provides a controlled speed of 10 to 40 rpm. A further reduction is speed to 0 to 2 rpm is accomplished through a worm gear drive. The worm is attached to the output shaft of the Zeromax drive and meshes with the toothed wheel attached to one of the bulkheads. The test procedure presently used is to load the specimen to a given biaxial stress state and then to subject the cylinder to torsion, recording the angle of rotation and the torque.

MEASUREMENTS AND DATA REDUCTION

The apparatus gives six output parameters, three forces and three deformations. The forces are axial forces, pressure and torque, and the deformations are the axial elongation, expansion of the cylinder circumference and angular rotation of the cylinder end. In the following paragraphs we will describe the means used to measure and record these parameters and the procedure used to reduce them to the desired stress and strain results.

The axial load and elongation are measured and recorded in the manner provided by the Instron testing machine. That is, the axial load is measured with the Instron load cell, which is a strain gage device with a number of load ranges available through the electronics provided with the testing machine. The magnitude of the load as the test proceeds is continuously recorded on the strip chart recorder that is part of the Instron system. The axial elongation is measured and recorded by the synchronized motions of the cross-head and the strip chart recorder so the elongation corresponding to any force magnitude is proportional to the distance the chart moves, while the load increases to that magnitude. Said in a different way, the resulting curve on the strip chart recorder is an axial load-elongation plot. The axial load, F, and elongation, e_a, are converted to axial stress, T_a, and strain, E_a, by the following expressions:

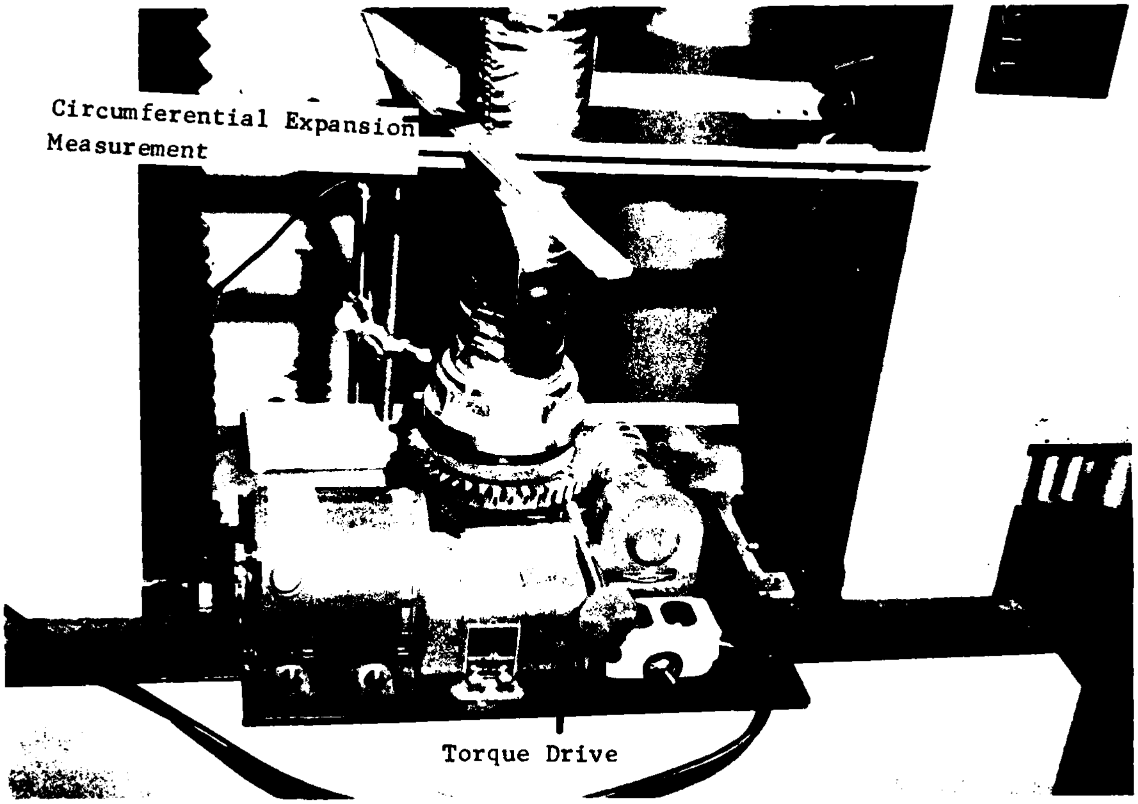

FIGURE 8. DETAIL OF THE TORQUE DRIVE AND THE CIRCUMFERENTIAL EXPANSION MEASUREMENT

$$T_a = F/C_o + r_o(1 + E_c)^2 \ P/2 \qquad (6)$$

$$E_a = e_a/l_o \qquad (7)$$

In these expressions C_o, r_o, l_o, P and E_c are respectively the undeformed circumference, radius and length of the cylinder, the pressure and the circumferential strain. These are engineering stresses and strains based on the undeformed geometry of the cylinder. The circumferential strain gets into the formulas through the computation of the axial force due to internal pressure where it is believed to be correct to use the deformed radius of the cylinder.

For determination of the circumferential stress and strain, the pressure and expansion of the cylinder circumference are measured and recorded. The pressure in the cylinder is measured with a high output pressure transducer, Model DV, from BLH Electronics. The location of this transducer is shown in Figure 9. This is a strain gage transducer with a self-contained regulated power supply and amplifier. One of these transducers rated for 0.34 mPa is used for lightweight fabrics, and one rated for 3.45 mPa is used for heavyweight fabrics. The output of the pressure transducer is recorded on one channel of a two-channel Linear Recorder, Model 385. The technique for measurement of the expansion of the circumference is shown in Figures 8 and 10, where we have a string fixed in place at a point in front of the cylinder, wrapped around the cylinder, and connected to a motion transducer in back of the cylinder. The fixed point and the connection point on the motion transducer form a line which is tangent to the cylinder. A linear variable differential transformer, Model 2000 DC–D of the Schaevitz Engineering Company, is used as the motion transducer and the output from this device is recorded on the second channel of the Linear recorder. The circumferential stress, T_c, and the circumferential strain, E_c, are computed from the Pressure, P, and the circumferential expansion, ΔC, by the expressions:

$$T_c = r_o(1 + E_c)(1 + E_a)P \qquad (8)$$

$$E_c = \Delta C/C_o \qquad (9)$$

The parameters r_o, C_o, P, and E_a are respectively the radius and circumference of the undeformed cylinder, the pressure, and the axial strain. As with the axial stress and strain these are engineering quantities, and the strain enters the calculation as a result of computing the total force acting on a circumferential line due to the pressure.

For the torsion of the cylinder the torque and the angular rotation of the end of the cylinder must be measured. A torque cell was made and located on the fixed bulkhead as shown in Figure 9. This torque cell consists of an aluminum cylinder with two pairs of shear torque strain gages mounted with Eastman 910 cement on its surface. The stain gages which form a complete bridge are BLH No. FAED–25B–35–S13–EL gages. The aluminum cylinder has a diameter of 3.2 cm and the gage length is 0.635 cm. This load cell proved to be sufficiently sensitive to measure the rather small torques involved in the torsion of fabric cylinders under biaxial load. The output from this torque cell is recorded on the second channel of the Instron strip chart recorder. The angular rotation of the free end of the cylinder is not measured electronically. The torsion test is conducted by rotating the end of the cylinder through an angular increment and stopping to record data. The angular increment is measured

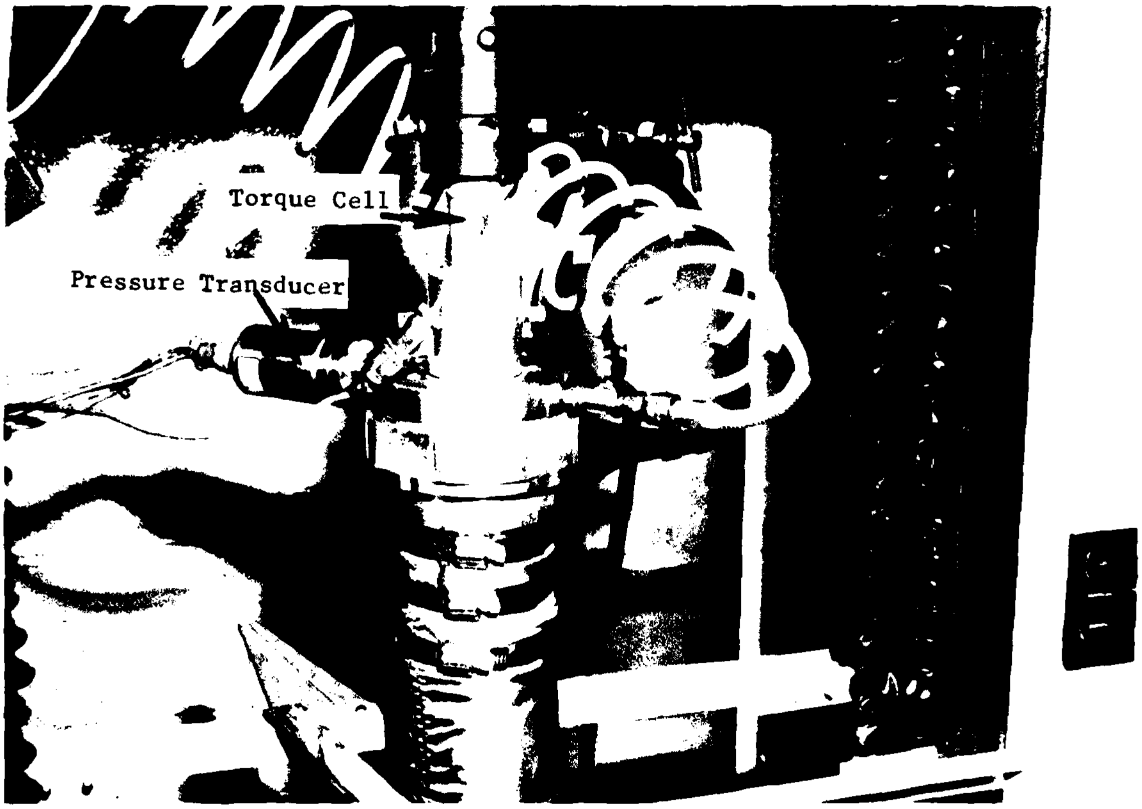

FIGURE 9. DETAIL SHOWING LOCATION OF PRESSURE TRANSDUCER AND TORQUE CELL.

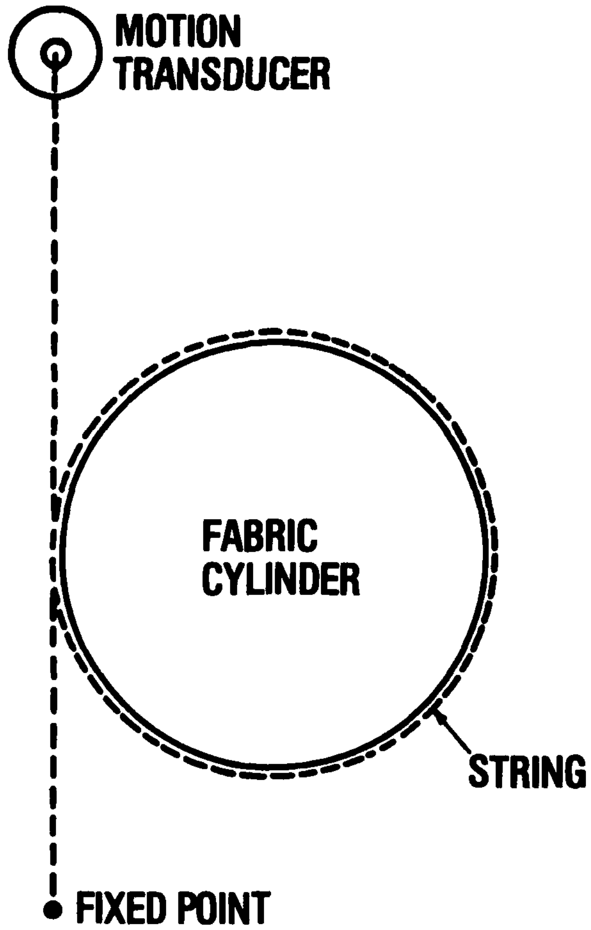

FIGURE 10. SCHEMATIC OF TECHNIQUE FOR MEASURING EXPANSION OF THE CYLINDER CIRCUMFERENCE

using marks on the moving bulkhead and a fixed pointer. The shear stress, τ, and shear strain, γ, are computed from the torque, M, and the angle of rotation, θ, by the following expressions:

$$\tau = M/2\pi r_o^2 (1 + E_c) \tag{10a}$$

$$\gamma = \theta r_o / l_o \tag{10b}$$

As before r_o, l_o, and E_c are the radius and length of the undeformed cylinder and the circumferential strain.

DESCRIPTIVE SUMMARY OF THE BIAXIAL AND SHEAR STRESS–STRAIN TESTING APPARATUS

The present instrument with all of its component parts is illustrated in Figures 11 and 12. The functions of the components identified in the figures are as follows:

a. Figure 11. Rear View of Testing Apparatus:

(1) The measuring string measures the increase in circumference of the test cylinder due to increasing air pressure in the cylinder. One end of the string is fixed and the free end is wrapped around the test cylinder, and connected to the position transducer.

(2) The position transducer transmits the electronic signal to a recorder indicating the take-up in length of the measuring string due to the increase in circumference of the test cylinder.

(3) The pressure transducer measures the air pressure in the test cylinder and transmits the signal to the biaxial ratio control box which compares the signal with the amplified signal from the Instron load cell. A match of the two signals can be set at different levels, permitting tests to be run at different stress-strain ratios.

b. Figure 12. Front View of Testing Apparatus:

(1) The moving cross-arm applies an axial strain (elongation) to the fabric cylinder.

(2) The Instron load cell measures the axial load applied to the fabric cylinder.

(3) Pressure valve controls the level of air pressure introduced into the fabric cylinder according to the signal from the biaxial control box.

(4) The mounted test specimen shown is self explanatory.

(5) The torque drive mechanism rotates one end of the cylinder.

(6) The two-channel Instron recorder is used to record the axial load applied to the cylinder on one channel and the increase in circumference of the cylinder due to increasing air pressure on the other. The distance the chart moves is proportional to the elongation of the cylinder.

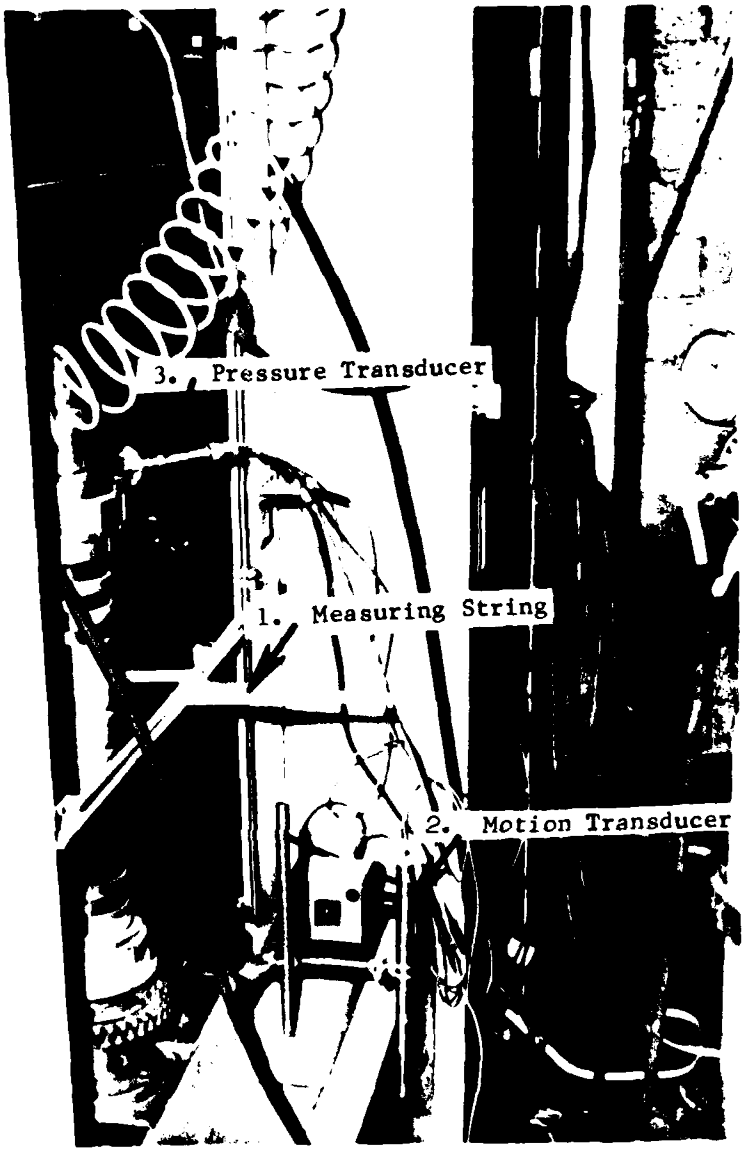

FIGURE 11. REAR VIEW OF TESTING APPARATUS

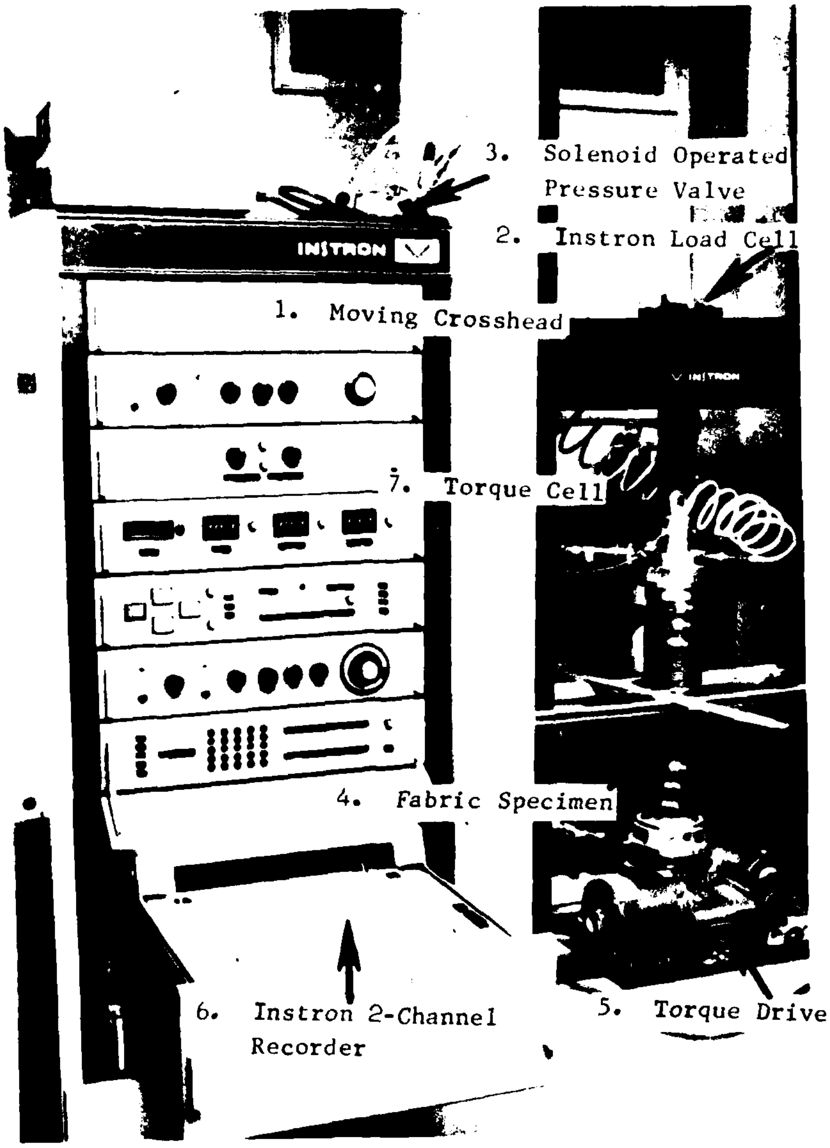

FIGURE 12. FRONT VIEW OF TESTING APPARATUS

(7) Torque cell measures the torque applied to the cylinder. The shear stress in the fabric can be calculated from the measured torque.

The construction of this unit was one of the primary objectives of these efforts. However, in order to complete the overall objective of the project in all respects, it is necessary to establish a uniform test procedure and conduct an evaluation of the capability of the instrument.

EVALUATION OF CAPABILITY

The purpose here is to present some results obtained using the above-described testing apparatus and compare these results with results obtained with other approaches. This comparison provides a means of evaluation of the apparatus developed. This is done both for the strength of the fabrics and for their stress-strain behavior. Comparisons for the torsion or shear behavior are not included, as none are available.

Test Fabrics

We begin by describing the fabrics used in this evaluation. To fully define the capability of the apparatus by performing fabric tests it is necessary to obtain and evaluate fabrics covering the entire range of fabric weights required for military items. The fabrics selected are a low weight material of 34 g/m^2 as used for parachutes, a medium weight material of 266 g/m^2 as used for tentage, a high weight material of 486 g/m^2 required for body armor, flak curtains, and possibly air-supported structures. Except for the one cotton fabric (the current standard cotton tent duck fabric), the fabrics are woven with continuous filament fibers of either nylon or polyester. The fabrics differ in construction *relative to yarn size, yarn twist, weave, and* ends and picks per meter. The construction of the four fabrics given above is shown on Table 5. The fabric numbers shown on this Table refer to identification numbers used in the test program. It should be noted that the polyester tent-type fabric referred to as Fabric #16 is a commercial fabric not covered by any military specification. The last column in Table 5 provides information on maximum weavability of fabrics in percent. One hundred percent means that the maximum number of yarns of a given size that can be woven side by side in a fabric has been attained. Any number less than 100% means that the weave does not have the maximum tightness. With cotton duck, maximum tightness is necessary for effective water repellency after finishing. One point of interest that should be noted is that the cotton duck in the grey state has achieved a tightness in weave nearing 100%, which has been relaxed somewhat in finishing this fabric from 99 to 95%. This means that the finished duck is not as tight as it might be for effective water repellency at minimum weight. More finish will have to be used to achieve the desired objective.

Test Results

In this section we will present results on the strength of each of the fabrics described above and on the stress-strain behavior of the parachute and polyester tent-type fabrics. The strength data obtained with the apparatus described here and referred to as the cylinder test will be compared with uniaxial and other biaxial test results. The uniaxial test results were obtained using one-inch ravel strip specimens. The biaxial results used in this comparison were

TABLE 5

Construction Parameters of Test Fabrics

Specification Number	Fiber Type	Use	Yarns/m Warp Ends/m	Yarns/m Filling Pick/m	Yarns Size kg/m (Denier) Warp	Yarns Size kg/m (Denier) Filling	Yarn Twist Turns per Meter Warp	Yarn Twist Turns per Meter Filling	Crimp Percent Warp	Crimp Percent Filling	Weave	Maximum Weavability Percent
MIL-C-7020 (Fabric #1)	Nylon	Parachutes	4.96×10^3	4.96×10^3	3.0×10^{-6} (30)	3.0×10^{-6} (30)	20 Z[a]	20 Z[a]	1.5	1.5	Plain Ripstop	100
None (Fabric #16)	Polyester	Tent Type	3.6×10^3	1.76×10^3	2.48×10^{-5} (248)	6.91×10^{-5} (691)	200 Z[a]	200 Z[a] 80 S[b]	7.0	0.7	Plain	95
MIL-C-43627	Cotton FWWMR	Tentage	2.0×10^3	1.6×10^3	7.07×10^{-5} (707)	5.87×10^{-5} (587)	440 S[b]	320 S[b]	16.0	4.7	Plain	99[c] 95[d]
MIL-C-12369 (Fabric #6)	Nylon	Body Armor	1.92×10^3	1.76×10^3	1.05×10^{-4} (1050)	1.05×10^{-4} (1050)	140 Z[a]	140 Z[a]	9.0	6.0	2 x 2 Basket	100

[a] Twist single yarns mostly 'Z' righthand twist

[b] Twist ply yarn, mostly 'S' lefthand twist

[c] Unfinished gray duck

[d] Fire, water, weather and mildew resistant (FWWMR) finished duck

obtained using the cruciform biaxial tester described in reference 4. The uniaxial strength results are the average of from five to ten tests, while the biaxial results from both the cruciform and the cylinder tests are from a single test.

Fabric Strength

The results for the strength of the four fabrics are presented in Tables 6 to 9 which give the breaking stress and strain for each of the three test methods. In certain specified cases the fabrics could not be tested to rupture, and for these cases we present corresponding states of stress and strain obtained by the two biaxial test methods for comparison.

The results for the parachute fabric are presented in Table 6 and these data show that both biaxial stress tests with a 1/1 stress ratio have the warp and filling stresses at failure nearly equal but somewhat lower than those obtained with the uniaxial test. The uniaxial test data, as expected, show a good strength balance in the warp and filling direction. It is suggested that the reason for this is the construction of the fabric as shown in Table 5. The fabric has an equal number of ends and picks per meter of fabric. The yarn twist was low just enough to have the individual yarn filaments react as a coherent mass to an applied load. Finally, the crimp in both yarn directions is low due primarily to the thin yarns used to make the fabric. Low yarn twist and low yarn crimp are contributing factors to maximum fabric strength at the lowest possible fabric weight.

The balanced construction of the parachute fabric, i.e., the same yarn size, an equal number of ends and picks per meter and the same low crimp in the warp and filling direction, will provide maximum-strength fabrics at the lowest possible weight for inflated spherical structures. However, the same fabric would not be as weight-efficient if used for inflated cylindrical structures where the loading ratio is 2/1. The parachute fabric was tested on both the cruciform and cylinder biaxial stress-strain testing machines using a 2/1 loading ratio. The test results indicate that when the fabric fails, the stress on the warp is twice that of the filling, reflecting the ratio of the stresses on the two yarn systems. This indicates that for the inflated cylindrical structures the weight of this fabric could be reduced without impairing its functional performance. In addition, the rupture stress of the warp in a 2/1 stress ratio test is higher than that with the 1/1 stress ratio and is approaching the rupture stress attained with the uniaxial tests. This suggests that biaxial stresses at an equal level in both directions are more severe on the fabric system than when the stress in one direction is greater than that in the other. It will also be noted that the rupture stresses obtained with the cylinder test are different from those obtained with the cruciform test, suggesting a difference between the two test methods. However, with the extremely small quantity of data available, one test from each test method, such conclusions as these are at best tenuous.

The strength results for the non-specification polyester fabric are presented in Table 7. This is called a tent-type material solely on the basis of its strength and weight which are typical of fabrics used for tentage. It can be seen from Table 5 that this fabric is not of a balanced construction. There are twice the number of warp ends per meter as there are filling picks. The filling yarns are three times the size of the warp yarns. Both warp and filling yarns are highly twisted. The warp is highly crimped while the filling yarns lie almost

TABLE 6

Comparison of Fabric Strength Determinations by Three Methods

MIL–C–7020 Parachute Fabric (Fabric #1)

Test Method	Stress, N/cm Warp	Stress, N/cm Fill	Strain, % Warp	Strain, % Fill	Stress Ratio σ_w/σ_f
Uniaxial	81		21.2		
		84		29.5	
Cruciform	54	62	12.5	18.0	1/1
	76	38	17.5	12.5	2/1
Pressurized Cylinder	60	63	12.5	21.0	1/1
	67	33	15.5	9.0	2/1

Fabric density – 34 g/m^2

Fiber Tenacity – 7.0 g/denier

TABLE 7

Comparison of Fabric Strength Determinations by Three Methods

Polyester Tent-Type Fabric (Fabric #16)

Test Method	Stress, N/cm Warp	Stress, N/cm Fill	Strain, % Warp	Strain, % Fill	Stress Ratio σ_w/σ_f
Uniaxial	363		25.5		
		650		14.1	
Cruciform	380	380	21.5	6.5	1/1
	200	200	15.0	3.5	1/1*
Pressurized Cylinder	205	200	14.8	4.8	1/1*

Fabric density — 232 g/m^2

Fiber tenacity — 8 g/denier

*Test not carried to break

TABLE 8

Comparison of Fabric Strength Determinations by Three Methods

MIL-C-43627 Tentage Fabric (FWWMR Cotton Duck)

Test Method	Stress, N/cm Warp	Stress, N/cm Fill	Strain, % Warp	Strain, % Fill	Stress Ratio σ_w/σ_f
Uniaxial	180		15.5		
		220		12.0	
Cruciform	145	140	10.5	6.8	1/1
Pressurized Cylinder	180	183	14.0	8.3	1/1

Fabric density – 562 g/m^2

Fiber tenacity – 2.8 g/denier

TABLE 9

Comparison of Fabric Strength Determinations by Three Methods

MIL–C–12369 Body Armor Fabric (Fabric #6)

Test Method	Stress, N/cm Warp	Stress, N/cm Fill	Strain, % Warp	Strain, % Fill	Stress Ratio σ_w/σ_f
Uniaxial	1286		49.2		
		1383		41.9	
Cruciform	700	1340	21.5	25.5	1/2
	140	273	6.0	10.5	1/2*
Pressurized Cylinder	140	270	3.5	13.0	1/2*

Fabric density – 486 g/m^2

Fiber tenacity – 7.5 g/denier

* Test not carried to break

straight in the fabric. From Table 7 the uniaxial tensile tests indicate that the rupture stress in the warp direction is somewhat greater than half that found for the filling direction. However, when the fabric is tested to failure using the biaxial cruciform method with a 1/1 stress ratio, the stresses in the warp and filling direction were the same when rupture occurred. This was expected because of the stress ratio used under the condition of a 1/1 stress ratio, the weaker yarn system in the fabric will fail before the full strength potential of the stronger yarn system could be realized. Also, the rupture stress for the biaxial cruciform method is somewhat higher than that of the warp direction for the uniaxial test. The polyester tent-type fabric could not be tested to rupture with the cylinder method of test due to seam difficulties. The fabric was tested on the cylinder testing machine to slightly over 50% of the rupture stress obtained by the cruciform method of test. The seam was still intact at the time when the test was completed. The data from this test is shown on Table 7. Also shown is data taken from the cruciform test made on this fabric at the same stress level and stress ratio used for the cylinder test. It can be seen that good agreement was found in the strains between the two methods of biaxial stress-strain tests.

The third fabric tested is the current standard Army duck fabric with the FWWMR treatment and the strength results from these tests are presented in Table 8. This fabric was selected to show the levels of failure stress found for the material used for standard Army tents as measured with the instruments included in this study. It can be seen on Table 8 that good agreement was found between the rupture stresses obtained by the uniaxial and the biaxial cylinder method of test. The reason for the lower values of stress and strain at failure obtained by the cruciform method is not understood at this time.

The results from the fourth fabric, the nylon ballistic material, are presented in Table 9 and show good agreement between the uniaxial rupture strength for the filling direction and the filling stress at rupture with the cruciform method. The difference in the stresses sustained by the warp and filling yarn systems at rupture reflect the 1/2 loading ratio with the greater load applied to the filling yarns. The ballistic fabric could not be tested to break with the cylinder method of test because of seam failures. In the cylinder test the fabric is loaded to approximately 20% of its uniaxial breaking load. The strain results obtained with the cylinder method are in good agreement with those obtained with the cruciform method at the same stress level and stress ratio.

These results demonstrate that the biaxial and shear stress-strain apparatus is capable of measuring the strength of fabrics and that the results are in general agreement with other test methods. A limitation on the testing of the higher strength fabrics due to cylinder seam strength was also found, and improved seaming techniques are being sought.

Stress-Strain Behavior

In the design of fabric structures the fabric strength is needed for the final design criteria, but for the part of the design process involving the computation of the stresses in a fabric structure, the complete stress-strain behavior is needed. In this section of the report we present some results to demonstrate the capability of the biaxial and shear stress-strain testing apparatus in producing such data.

In Figures 13 and 14 are present some representative stress-strain curves for the parachute fabric and the polyester tent-type fabrics obtained with the cylinder apparatus along with companion results from the cruciform apparatus for comparison. For the parachute fabric the results presented are for a 2/1 stress ratio and the cylinder and cruciform results are in good agreement for both the warp and fill directions. For the polyester tent-type fabric the results are for a 1/1 stress ratio and here also the agreement between the cruciform and cylinder results is good. These results show the fill direction much stiffer than the warp, reflecting the fact that while the fill direction has fewer yarns per meter than the warp direction, the fill yarns are much heavier than the warp yarns. The results presented in Figure 15 illustrate one of the difficulties in obtaining and interpreting stress-strain results of fabrics. In this figure we have the warp stress-strain behavior for a number of repeated tests on the same specimen of the polyester tent-type fabric, and we find that the behavior changes significantly as the number of tests increases, although it does become reasonably repeatable after three or four tests. In the use of such data, it is necessary to know the situation in which the fabric will be loaded and to use the appropriate data. That is, if the fabric will be subjected to repeated loadings in use, then design analysis should use stress-strain data obtained after several tests. It should be pointed out that the results for test #1 in Figure 15 correspond to the cylinder results in Figure 14. The cruciform results in Figure 14 are also from the first test of that specimen.

The capability of the apparatus described in this report, that makes it different from the cruciform apparatus described in reference 4 and most other biaxial testers, is its ability to determine the shear behavior of fabrics in the presence of a biaxial stress state. An example of the results obtained using this capability is presented in Figure 16 where we present plots of shear strain as a function of shear stress for a variety of biaxial stress levels and ratios for the parachute fabric. These data were obtained using the following test procedure: The specimen was put in a specified biaxial stress state, level, and ratio, and kept in that state while the cylinder was rotated through an angular increment and stopped while a torque reading was made. After reading the torque, rotation through an additional increment was made and stopped so the torque could be read. This was continued until the four data points for each biaxial stress state shown on Figure 16 were obtained, at which time the specimen was unloaded and this test procedure carried out for the other biaxial stress states. The results in Figure 16 show a linear relationship between shear stress and strain for a given biaxial stress state, but one should be slow to generalize this results. As is expected the shear stiffness increases with increasing biaxial stress level and also appears to increase as the stress ratio T_w/T_f increases. No comparable results from other apparatus are available for comparison with these shear stress-strain results.

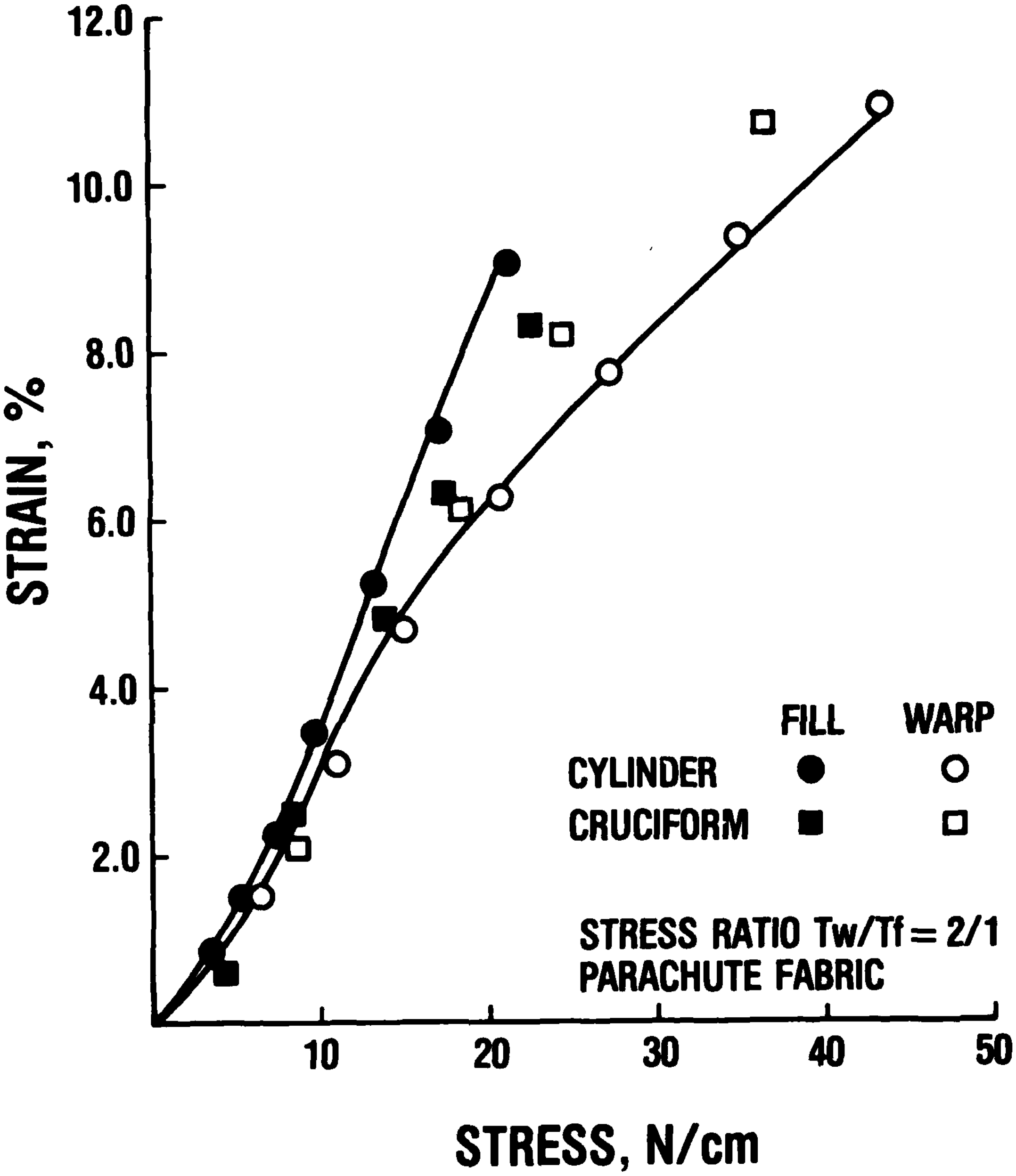

FIGURE 13. BIAXIAL STRESS-STRAIN BEHAVIOR OF THE PARACHUTE FABRIC.

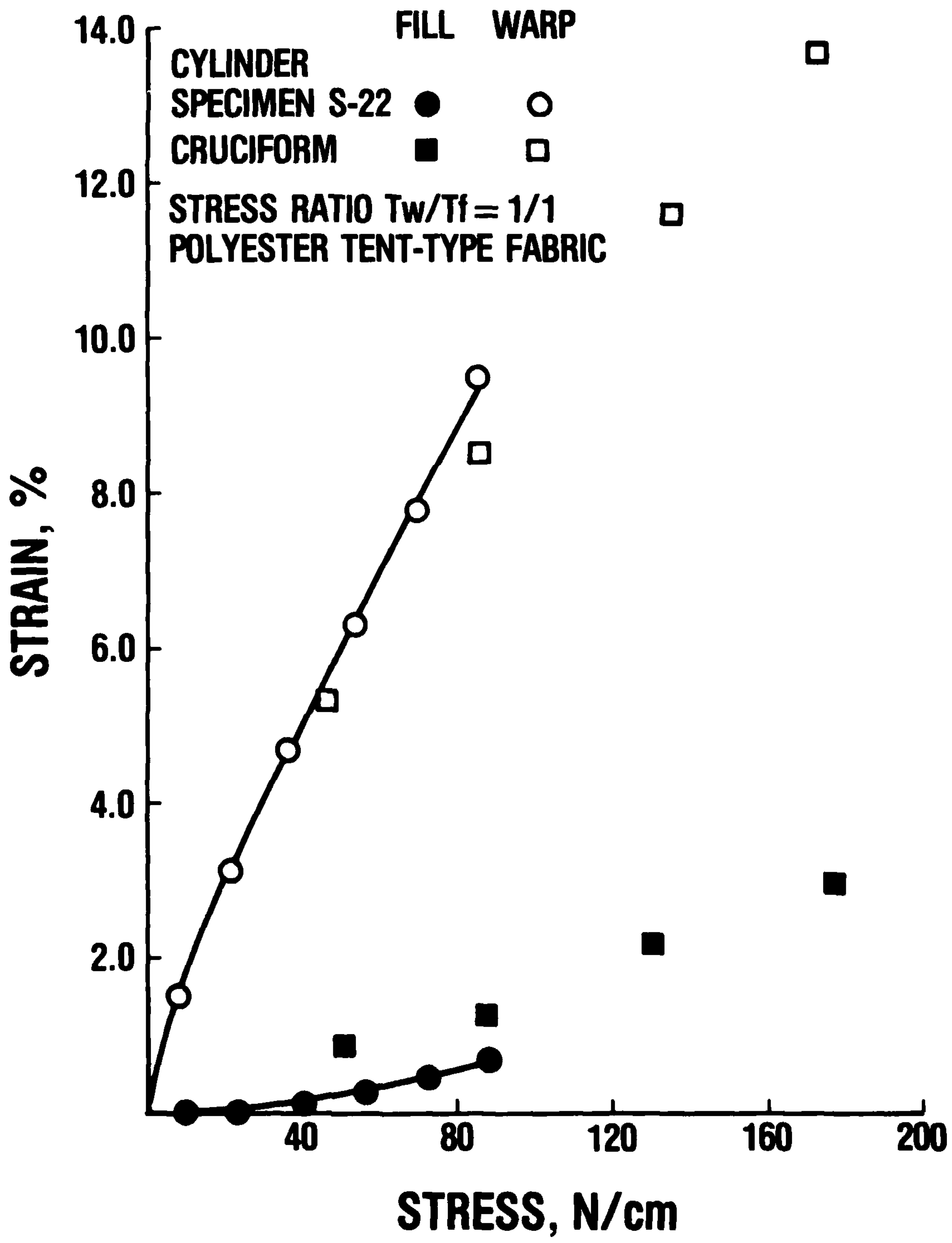

FIGURE 14. BIAXIAL STRESS-STRAIN BEHAVIOR OF THE POLYESTER TENT-TYPE FABRIC.

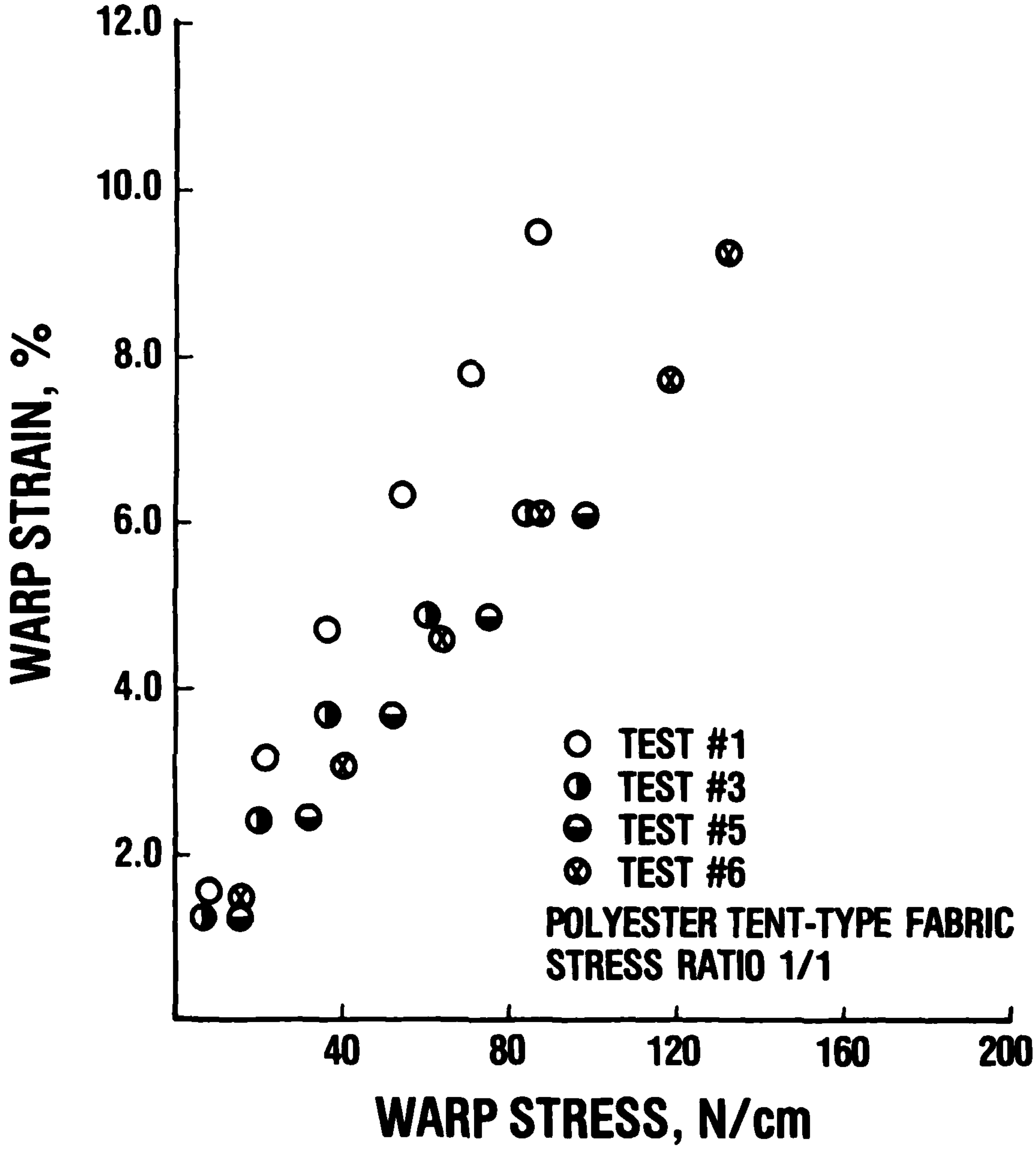

FIGURE 15. BIAXIAL STRESS-STRAIN BEHAVIOR FROM REPEATED TESTS ON SAME SPECIMEN.

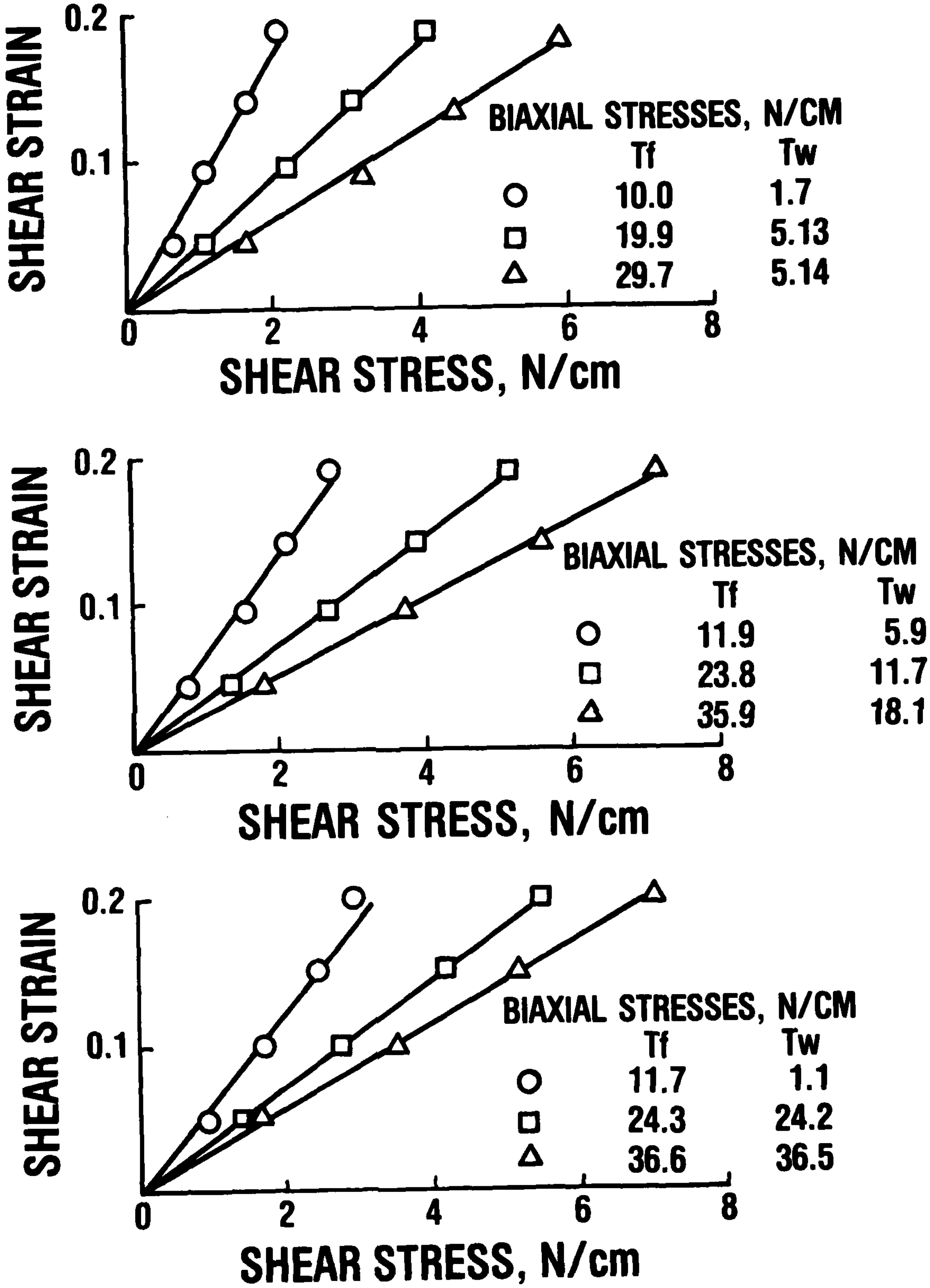

FIGURE 16. RESULTS FOR SHEAR STRESS-STRAIN BEHAVIOR OF THE PARACHUTE FABRIC

CONCLUSIONS

A biaxial and shear stress-strain testing apparatus for fabrics and films has been designed and constructed. This apparatus has been used to test fabrics ranging in weight from a 34 g/m^2 lightweight parachute fabric to a 486 g/m^2 ballistic fabric. The apparatus has been used successfully to test lightweight and some medium-weight (250 g/m^2) tent fabrics to rupture. These rupture stresses were found to be in general agreement with uniaxial and other biaxial rupture stresses. Heavyweight and some medium-weight fabrics could not be tested to rupture because of failures in the seam of the test cylinder. This problem is not insurmountable, and techniques are being developed to sew stronger seams. The apparatus has also been used to obtain the stress-strain behavior of fabrics for both biaxial stress states and shear stresses in the presence of a biaxial stress state. The biaxial stress-strain behavior obtained with this apparatus is in good agreement with that from other apparatus. Thus, the apparatus at its present state of development can be used to provide useful stress-strain data on all fabrics and strength data on light- and medium-weight fabrics. These data can be related to fabric construction details which, in turn, can be used to insure conformity of the product. The apparatus, within the now-existing limitations stated, can be used to provide the information necessary for the design of structural fabrics, the drafting of improved procurement specifications for fabrics, and the qualification of new fabrics for military use.